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WO 94/13017 A1 US 5378912 A US 5323040 A

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(54) SiC semiconductor device

(57) A semiconductor device structure having an epitaxial layer 12, formed of silicon for example, is disposed on a high band-gap material 11, such as silicon carbide, which is in turn disposed on a semiconductor substrate 10, such as silicon. The high band gap material achieves a charge concentration much higher than that of a conventional semiconductor material for the same breakdown voltage. This structure may be used in a MOSFET or a diode. The region 11 is a drift region of lower resistance than silicon and provides a higher critical avalanche field. The MOSFET may be of the trench type with a polysilicon gate.

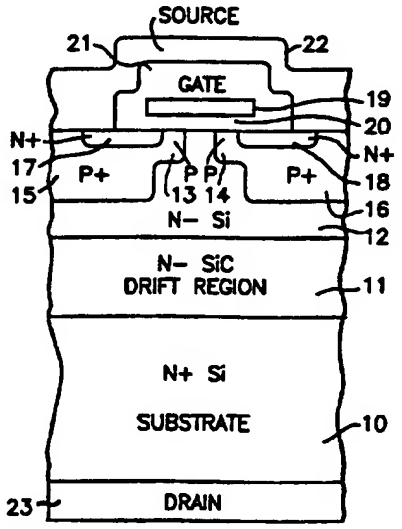

FIG. 1

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

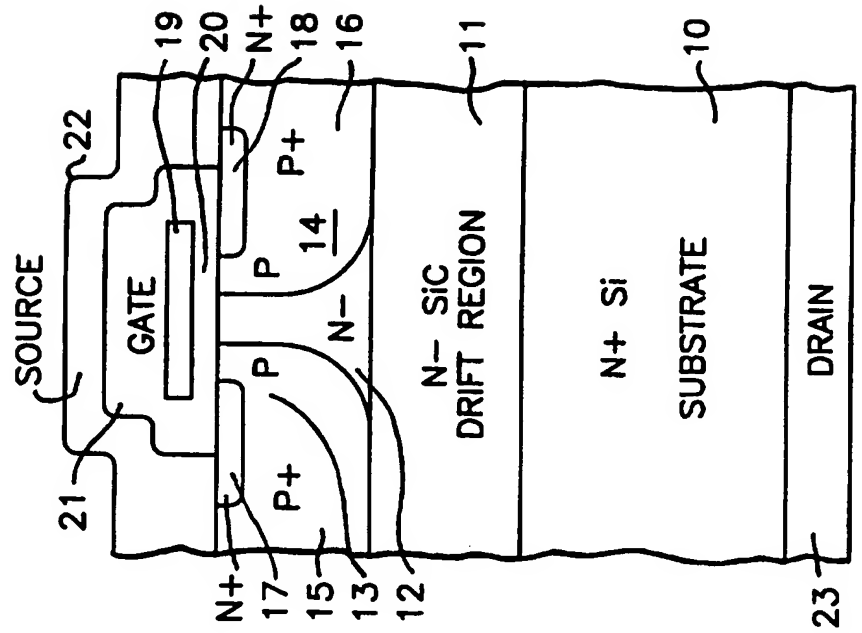
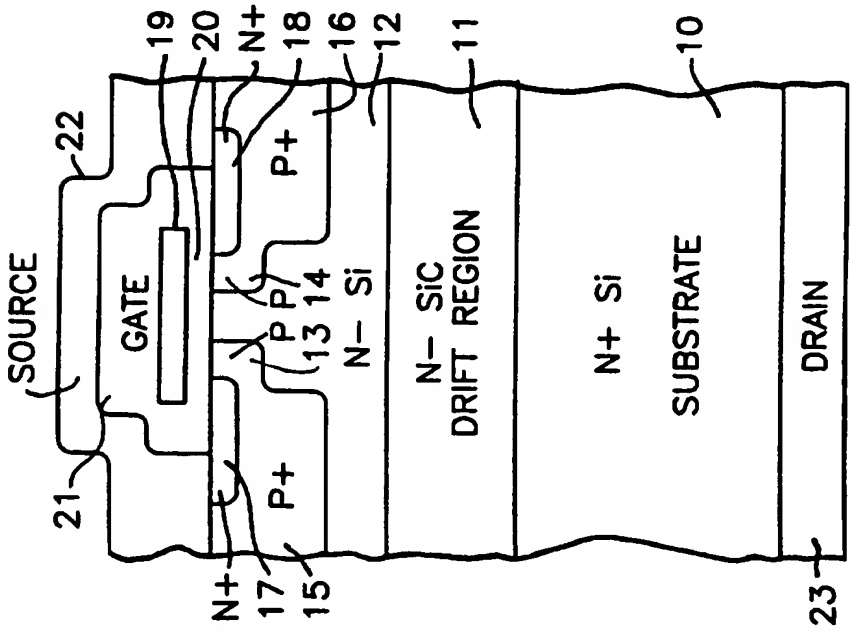

SOURCE
GATE
21
22
19
20
N+
18
16
P+
P
14
N-
P
P+
N+
17
15
13
12
N- SiC
DRIFT REGION
11
N+ Si
SUBSTRATE
10
DRAIN
23

FIG. 4


SOURCE
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DRIFT REGION
11
N+ Si
SUBSTRATE
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FIG. 1

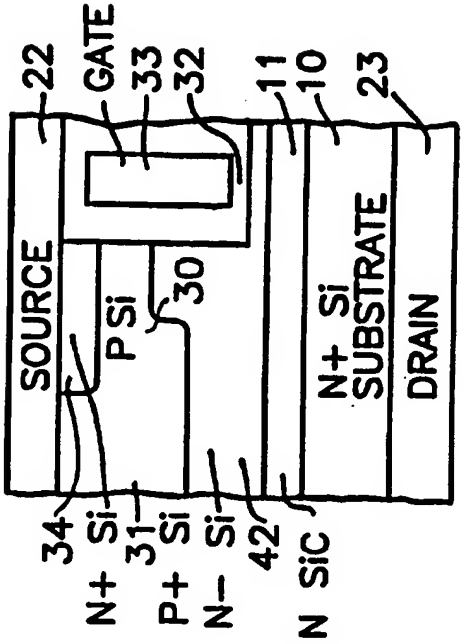

FIG. 3

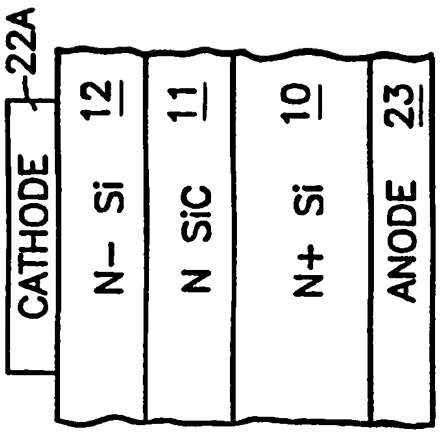

FIG. 2

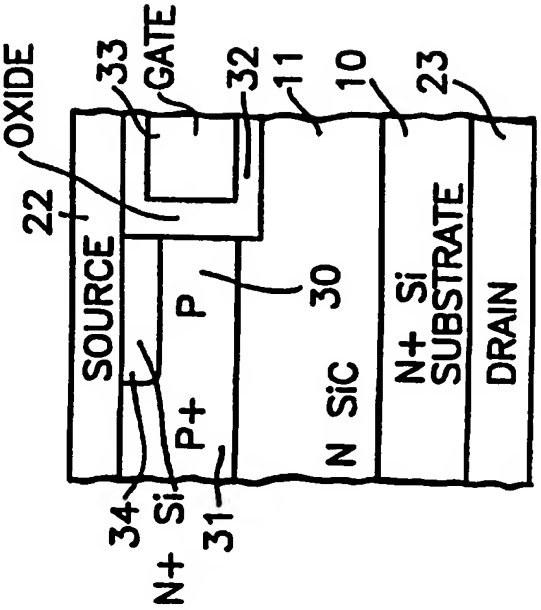

FIG. 5

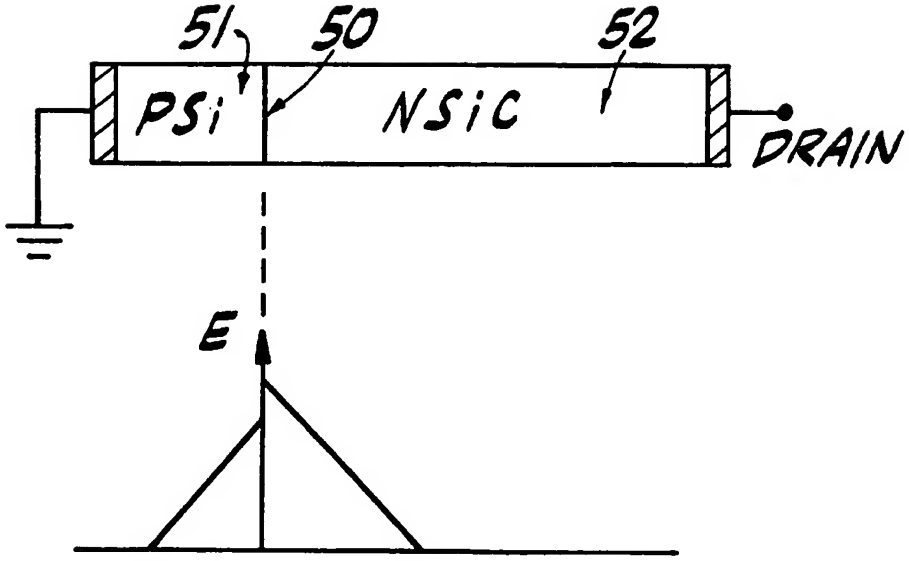

FIG. 6

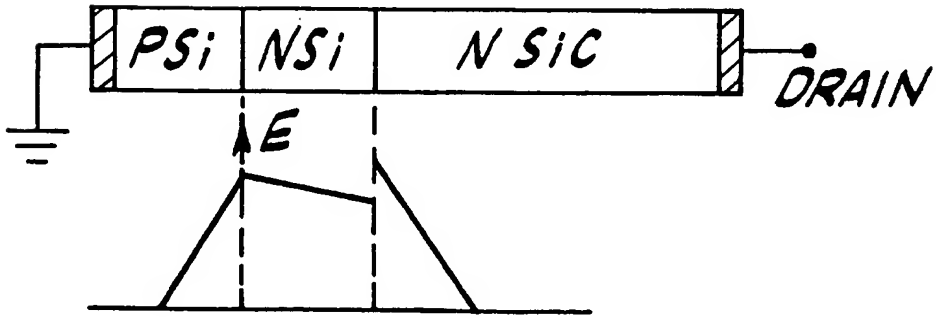

FIG. 7

SiC SEMICONDUCTOR DEVICE

This application claims the benefit of U.S. Provisional Application Serial No. 60/004,983 filed on October 10, 1995.

This invention relates to semiconductor devices. Specifically, this invention relates to high voltage semiconductor devices. More specifically, this invention relates to semiconductor devices requiring high conductivity and high breakdown voltages.

Silicon carbide (SiC) has a higher band gap than silicon (Si) and, hence, SiC has a higher critical avalanche electric field than Si with a potential of 100 times higher performance compared to silicon for high voltage devices. Specifically, 3C-SiC has about a 4 times higher critical avalanche electric field than Si; 6H-SiC has about an 8 times higher critical avalanche electric field than Si; and 4H-SiC has about a 10 times higher critical avalanche electric field than Si. The high critical electric field of SiC allows for higher doping and thinner drift regions thereby reducing the on-resistance of SiC power devices as compared to conventional Si power devices.

However, a problem currently exists with SiC devices, namely, that it is difficult to diffuse dopants

into the SiC material. Specifically, the diffusion of dopants into SiC requires temperatures in the range of 1800°C. Another problem with the use of SiC is that the material exhibits low MOS channel carrier mobility and, therefore, when SiC is used as a channel material in a semiconductor device, the conductivity of the channel may be degraded.

The present invention overcomes the deficiencies in the prior art detailed above by providing a semiconductor structure which includes a thin epitaxial layer of Si on a body of SiC material. It is preferred that the thin epitaxial layer be about 3 μm thick. The structure of the present invention may be used in a power MOSFET, a trench power MOSFET, a diode, and other semiconductor devices.

To reduce cost, the SiC layer can be formed on a highly doped Si substrate (3C-SiC has been reported in literature to be easily grown on Si). These structures, for example a power MOSFET having an epitaxially grown silicon layer, may be produced in an existing silicon power MOSFET fabrication facility using existing processes.

The drift regions of devices employing the structure of the present invention (such as power MOSFETs) consist mainly of SiC and, since the doping of SiC can be much higher than that of Si (while supporting the same voltage as a conventional Si device), the new device structures of the present invention provide lower on-resistances as compared to conventional Si power devices. It should be noted, however, that the breakdown voltages of device structures of the present invention

are still determined by the critical field at the P body/N^- drift region junction formed at least partly in Si. For high-voltage devices (e.g., greater than 60 volts) the device structures of the present invention are expected to provide 20% - 90% lower on-resistances as compared to conventional Si devices.

In the new structures of the present invention, the P body/N^- drift region junction can be formed either completely in Si or at the Si/SiC hetero-junction. For greatest improvement, it is preferred that the Si layer be thinner and the P body diffusions be made such that the P body/N^- drift region junctions are formed in SiC. However, such structures require the diffusion of dopants into SiC at high temperatures and for long time periods as compared to the diffusion of dopants in Si.

It is noted that structures employing other high band-gap semiconductor materials can be used in place of the specified SiC material and still be embraced by the present invention.

Other features and advantages of the present invention will become apparent from the following description of the invention which refers to the accompanying drawings wherein:

Fig. 1 shows a cross-section of a power DMOSFET device employing a structure of the present invention;

Fig. 2 shows a cross-section of a Schottky barrier diode device employing a structure of the present invention;

Fig. 3 shows a cross-section of a trench power MOSFET device employing a structure of the present invention;

Fig. 4 shows a cross-section of an alternate embodiment of a power DMOSFET device employing a structure of the present invention;

Fig. 5 shows a cross-section of an alternate embodiment of a trench power MOSFET device employing a structure of the present invention; and

Fig. 6 shows a cross-section of a junction of P-type silicon and N-type silicon carbide and a corresponding E field distribution across the junction in accordance with the device of Fig. 4 of the present invention.

Fig. 7 shows a cross-section of higher voltage supporting junction of the device structure of Fig. 1 and corresponding E field distribution.

In the attached drawings, Figure 1 shows a new SiC power DMOSFET structure in accordance with the present invention in which an N type SiC drift region 11 is disposed on an N^+ Si substrate 10 of the conventional type. SiC region 11 is more highly doped than Si and, thus, SiC region 11 is less resistive than prior art Si drift regions while still maintaining a high breakdown voltage. A three micron thick N^- epitaxial layer 12 is grown on top of the SiC drift region 11. Conventional power MOSFET junctions (such as P^- channel regions 13, 14; P^+ body regions 15, 16; N^+ sources 17, 18; poly-silicon gate 19; gate oxide 20; inter-layer oxide 21; and overlying source contact 22) are disposed on the N^-

epitaxial layer 12. A drain contact 23 is disposed on the bottom of substrate 10.

With reference to Figure 6, it will be shown that the amount of charge in the SiC region 11 is more than 3 times that of silicon for the same breakdown voltage. Figure 6 shows a junction 50 of P type Si 51 and N type SiC 52 where the corresponding E-field is also provided. To get a lower on-resistance for the drift region compared to Si MOSFET, the drift region damping (N_D) for supporting the high voltage should be high and the drift region thickness (W) for supporting the high voltage should be small. In other words, the drift region should be capable of supporting the blocking voltage with high doping (N_D) and minimum thickness (W).

At the junction 50, Gauss' Law provides that the following equations are valid:

$$\epsilon_{Si} * E_{Si} = \epsilon_{SiC} * E_{SiC}$$

$$E_{Si} = (\epsilon_{SiC}/\epsilon_{Si}) * E_{SiC}$$

$$E_{Si} \approx 0.82 * E_{SiC}, \quad \text{for 3C-SiC}$$

$$E_{SiC} \approx 1.21 * E_{Si}, \quad \text{for 3C-SiC}$$

In general, for uniform doping in the drift region, the following relationships are valid:

$E_c = qN_DW_c/\epsilon$, where E_c is the critical avalanche breakdown field for this structure at breakdown

$E_{SiC} = 1.21 * E_{c.Si}$

$$\text{slope of E field} = \frac{dE}{dY} = \frac{qN_D}{\epsilon}$$

drift region doping, N_D, is proportional to $E_{drift.\ max}$

drift region thickness, W, is proportional ϵ.

The above equation indicates that for the E field to go down to zero in the shortest distance (for minimum drift region thickness W), the dielectric constant of drift region material (ϵ) should be as low as possible.

Thus, for higher drift region doping, the drift region should be made of material with higher critical avalanche field compared to silicon.

For smaller drift region thickness, the drift region should be made of material with lower dielectric constant compared to silicon.

SiC has a higher critical avalanche field and a lower dielectric constant compared to Si. Thus, SiC is well suited as a drift region material and for lowering the resistance of the drift region, the drift region should be made substantially of a material like SiC.

With reference to Figure 1, any desired topology can be employed in providing junctions in the N^- epitaxial layer 12, thereby obtaining other MOS gated devices in accordance with the present invention.

Figure 2 shows a Schottky barrier diode employing a structure in accordance with the present invention. Elements similar to those of Figure 1 have the same identifying numerals. The major differences between the structures of Figure 1 and Figure 2 are that (i) the region 12 has no junction (rather, a conventional guard ring can be used); and (ii) the cathode 22a is preferably a high work function material, such as molybdenum or the like. As discussed above, the amount of charge in the SiC material is much higher than that of Si for the same breakdown voltage and, therefore, the

conductivity of the device is improved over conventional devices having the same breakdown voltage.

Figure 3 shows a trench power MOSFET employing a structure in accordance with the present invention. Specifically, a P silicon layer 30 extending from a P^+ body 31 is disposed against a gate oxide 32 which lines the trench etched in the silicon. The trench is filled with a poly-silicon gate 33. An N^+ source diffusion region 34 is diffused into P regions 30, 31 and a source contact 22 is disposed on regions 31 and 34 and gate oxide 32. As discussed above, the amount of charge in the SiC material is much higher than that of Si for the same breakdown voltage.

The device of Figure 4 is an alternate embodiment of a MOSFET in accordance with the present invention and is similar to that of Figure 1. In the device of Figure 4, the P^+ bases 15 and 16 directly contact the SiC drift region 11, leaving a comparatively narrower epitaxial layer 12.

The device of Figure 5 is similar to that of Figure 3, except that the junction between the P^+ region 31, the P region 30 and the N type region 11 is formed at the Si/SiC hetero-junction.

Although the present invention has been described in relation to particular embodiments thereof, many other variations and modifications and other uses will become apparent to those skilled in the art. It is preferred, therefore, that the present invention be limited not by the specific disclosure herein, but only by the appended claims.

Claims:

1. A semiconductor device comprising:

a semiconductor substrate;

a high band-gap material forming a drift region disposed on the semiconductor substrate; and

an epitaxial layer of semiconductor material disposed on the high band-gap material.

2. The semiconductor device of claim 1, wherein the high band-gap material forming a drift region is a low dielectric constant, high carrier mobility material.

3. The semiconductor device of claim 1, wherein the epitaxial layer of semiconductor material is about three μm thick.

4. The semiconductor device of claim 1, wherein the semiconductor substrate material is silicon.

5. The semiconductor device of claim 1, wherein the high band-gap material forming a drift region is silicon carbide.

6. The semiconductor device of claim 1, wherein the epitaxial layer of semiconductor material is silicon.

7. The semiconductor device of claim 1, wherein the semiconductor substrate material is silicon, the high band-gap material forming a drift region is silicon carbide, and the epitaxial layer of semiconductor material is silicon.

8. A MOSFET semiconductor device comprising:

a doped semiconductor substrate;

a doped high band-gap material forming a drift region disposed on the doped semiconductor substrate; and

a doped epitaxial layer of semiconductor material disposed on the high band-gap material.

9. The MOSFET semiconductor device of claim 8, wherein the doped band-gap material forming a drift region is a low dielectric constant, high carrier mobility material.

10. The MOSFET semiconductor device of claim 8, wherein the epitaxial layer of semiconductor material is about three μm thick.

11. The MOSFET semiconductor device of claim 8, wherein the semiconductor substrate material is silicon.

12. The MOSFET semiconductor device of claim 8, wherein the high band-gap material forming a drift region is silicon carbide.

13. The MOSFET semiconductor device of claim 8, wherein the epitaxial layer of semiconductor material is silicon.

14. The MOSFET semiconductor device of claim 8, wherein the semiconductor substrate material is silicon, the high band-gap material forming a drift region is silicon carbide, and the epitaxial layer of semiconductor material is silicon.

15. A semiconductor diode comprising:

a doped semiconductor substrate;

a doped high band-gap material forming a drift region disposed on the doped semiconductor substrate; and

a doped epitaxial layer of semiconductor material disposed on the high band-gap material.

16. The semiconductor diode of claim 15, wherein the doped high band-gap material forming a drift region is a low dielectric constant, high carrier mobility material.

17. The semiconductor diode of claim 15, wherein the epitaxial layer of semiconductor material is about three μm thick.

18. The semiconductor diode of claim 15, wherein the semiconductor substrate material is silicon.

19. The semiconductor diode of claim 15, wherein the high band-gap material forming a drift region is silicon carbide.

20. The semiconductor diode of claim 15, wherein the epitaxial layer of semiconductor material is silicon.

21. The semiconductor diode of claim 15, wherein the semiconductor substrate material is silicon, and the high band-gap material forming a drift region is silicon carbide.

22. The semiconductor device of claim 1, in which the semiconductor device is a trench power MOSFET.

23. The semiconductor device of claim 1, further comprising power MOSFET junctions disposed above the epitaxial layer and including P^+ body regions, N^+ sources; a poly-silicon gate; gate oxide and an overlying source contact all disposed above the epitaxial layer.

24. The semiconductor device of claim 21, further including a drain contact disposed below the semiconductor substrate.

25. The semiconductor device of claim 8, wherein the high voltage supporting P body/N^- drift junction is formed at epitaxial layer/high band-gap material hetero-junction.

26. The semiconductor device of claim 8, wherein the high voltage supporting P body/N^- drift junction is formed in epitaxial layer with high band-gap material disposed deeper from surface compared to junction.

27. The semiconductor device of claim 8, wherein the high voltage supporting P body/N^- drift junction is formed at in high band-gap material with the epitaxial layer/high band-gap hetero-junction disposed shallower from surface compared to the P body/N^- drift junction.

The Patent Office

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Application No: GB 9621170.1 **Examiner:** Robin Hradsky
Claims searched: 1-27 **Date of search:** 18 December 1996

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): H1K (KCAV, KCAX, KBC, KNAX)

Int Cl (Ed.6): H01L 29/12, 29/78

Other: Online: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	WO94/13017 A1	Cree Res (page 5 line 36 to page 6 line 19)	1,2,4-9,11-16,18-21
X	US5378912 A	Philips (col 4 line 5 to line 41)	1,8,15
X	US5323040 A	North Carolina Univ. (col 5 line 36 to line 61)	1,2,4-9,11-16,18-21

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